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Engineering Bulletin
Composting

EPA

Purpose

Section 121 (b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) mandates the U.S. Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants as a principal element." The Engineering Bulletins comprise a series of documents that summarize the latest information available on selected treatment and site remediation technologies and related issues. They provide summaries of and references for the latest information to help remedial project managers, on-scene coordinators, contractors, and other site cleanup managers understand the type of data and site character-istics needed to evaluate a technology for potential applicability to their Superfund or other hazardous waste site. Those documents that describe individual treatment technologies focus on remedial investigation scoping needs. Addenda will be issued periodically to update the original bulletins.

Abstract

Composting is an emerging ex situ biological technology that is potentially applicable to nonvolatile and semivolatile organic compounds (SVOCs) in soils. It has been applied to polycyclic aromatic hydrocarbons (PAHs) and explosives. It has been found to be potentially effective in biodegrading heavier petroleum hydrocarbons and some pesticides. Composting is not generally employed to treat heavy metals or other inorganics, although it may be applicable to inorganic cyanides.

Composting processes utilize bulking agents, such as wood chips and straw, to increase the porosity of soil or sediment. Manure, yard wastes, and food-processing wastes are often added to increase the amount of nutrients and readily degradable organic matter. Inorganic fertilizers may be added to supplement available nutrients. These supplements encourage growth of indigenous microbial populations capable of degrading contaminants of concern. Depending on the site-specific cleanup goals, composting can be used as the sole treatment technology or in a treatment train.

Composting can be performed in windrows, where material is put into rows and periodically turned; in aerated static piles, where perforated pipes within the pile supply aeration; and in vessels, where material is periodically mixed inside an aerated containment vessel. Biopiles, which structurally resemble static pile compost systems with forced aeration, differ from compost piles in that bulking agents are not added. Biopiles are outside the scope of this Engineering Bulletin.

The main advantages of composting are its low capital and operating costs. Because of the low operating costs, it is economical to continue the composting process for long periods of time until an endpoint is reached (i.e., when target levels of contaminants are achieved or toxicity is sufficiently reduced). Other advantages are the enriched end-product and simplicity of design. Composting system components are readily available and can be set up quickly. The main disadvantages of composting are that it is a slow process and consistent temperature control throughout the compost is difficult to maintain.

As of August 1995, composting was being considered or implemented as a component of the remedy at two CERCLA, two Resource Conservation and Recovery Act (RCRA), one State, two other Federal facility, and three Canadian sites [1, p. 14][2][3]. Three of these sites have achieved their cleanup goals. This bulletin provides information on the technology's applicability, limitations, description, process residuals, site requirements, regulatory considerations, current or recent performance data, current status, and a source of further information.

Technology Applicability

Although composting of yard wastes and municipal wastewater sludges has been performed for decades, composting of soils contaminated with hazardous materials is still an emerging technology. Composting has been demonstrated to be effective in biodegrading PAHs [2] and explosives in soils during full-scale applications [4]. Other studies have indicated that composting is potentially effective in degrading or transforming petroleum hydro-carbons [1][5] and pesticides [6, p. 2566] to environ-mentally acceptable or less mobile compounds.

Despite these promising studies, the ability of composting to completely degrade man-made organic compounds has not been fully demonstrated. Although composting systems have been used to biodegrade hazardous compounds such as pesticides, PAHs, and explosives, few studies (mostly bench-scale) have provided mass balance closures or fully investigated all of the intermediate products, final products, and by-products of the composting process. In pilot- and field-scale studies, it is difficult to determine whether the contaminants of concern were degraded, sorbed to the compost mixture, volatilized, or incorporated as part of the humic fraction. The lack of mass balance closure and conclusive evidence of the fate of contaminants in field-scale applications is not unique to composting. Many other technologies (both ex situ and in situ) lack conclusive evidence of contaminant fate in field-scale applications.

In addition, the use of composting to remediate a specific site does not ensure that composting will be effective at all sites or that the treatment efficiency achieved will be acceptable at other sites. Treatability studies should be performed to determine the effectiveness of composting at a given site. Experts at EPA's National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio may be able to provide guidance during the treatability study and design phases or provide state-of-the-art facilities for performance of bench- and pilot-scale treatability studies. General design information for composting processes can be obtained from various references [7][8]. It is essential that the general design principles of conventional composting be followed during hazardous waste composting, since a healthy microbial population is required for contaminant degradation [9, p. 62]. It may be necessary to adjust the design, based on treatability study results, to compensate for the contaminant degradation rates and soil conditions at a given site.

Advantages of composting over other types of tech-nologies include relatively low capital and operating costs, simplicity of operation and design, and readily available components. Because of the low operating costs, it is economical to continue the composting process for long periods of time, if required, to reach the desired endpoint. Another advantage of composting is that the composted soil is enriched in nutrients and suitable for re-vegetation. Composting can also be integrated into a treatment train. Capital costs can be optimized by tailoring the level of process control to the contaminant type. For example, static pile composting may be sufficient for petroleum hydrocarbons, whereas an in-vessel system may be more appropriate for halogenated SVOCs.

The effectiveness of composting treatment systems on general contaminant groups is shown in Table 1. For this document, "effective" means that several of the contamin-ants listed in a group have been shown to be biodegradable in full-scale remedial applications. Biodegradability varies widely among compounds in many groups. Examples of constituents within contaminant groups are provided in "Technology Screening Guide for Treatment of CERCLA Soils and Sludges" [10]. Other contaminants for which composting is applicable may not be included in these categories. However, many of the other compounds will biodegrade like contaminants in these categories. For example, some explosives are chemically similar to com-pounds in the nonhalogenated SVOC category; therefore, composting is expected to degrade these compounds. Information in this table is provided as general guidance on effectiveness; consultation with technology experts and site-specific treatability studies are recommended.

Table 1 is based on the current available information or, if no information is available, professional judgment. The proven effectiveness of the technology for a particular site

Table 1
Effectiveness of Composting on General Contaminant Groups for Soil and Sludges

	Contaminant Groups[a]	Effectiveness[b]
Organic	Halogenated volatiles[c]	□
	Halogenated semivolatiles[d,e]	▼
	Nonhalogenated volatiles[c]	□
	Nonhalogenated semivolatiles[d]	■
	PCBs[d,e]	▼
	Pesticides[e,f]	▼
	Dioxins/Furans	□
	Organic cyanides	▼
	Organic corrosives	▼
Inorganic	Volatile metals	□
	Nonvolatile metals	□
	Asbestos	□
	Radioactive materials	□
	Inorganic corrosives	□
	Inorganic cyanides	▼
Reactive	Oxidizers	□
	Reducers	□

a See the "Technology Screening Guide for CERCLA Soils and Sludges" for a list of the contaminants in each group.
b For this document, "effective" means that several of the contaminants listed in a group are biodegradable.
c While these contaminants may be biodegradable, they would likely be volatilized before being degraded.
d Smaller, less halogenated compounds in this category are better candidates for composting.
e May require an anaerobic/aerobic cycle.
f Composting is not recommended for organometallic compounds.
□ No Expected Effectiveness: Expert opinion is that technology will not work.
▼ Potential Effectiveness: Expert opinion is that technology will work.
■ Demonstrated Effectiveness: Successful treatability test at pilot- or field-scale completed.

or waste does not ensure that composting will be effective at all sites or that the treatment efficiencies achieved will be acceptable at other sites, especially when a site is contaminated by several types of wastes. For the ratings in Table 1, Demonstrated Effectiveness means that, during full-scale applications, the technology degraded the parent compound for several contaminants within that particular contaminant group. Composting has been demonstrated to be effective in remediating PAHs and explosives in soils.

Ratings of Potential Effectiveness or No Expected Effectiveness are based upon the judgement of a panel of EPA and non-EPA experts. Where Potential Effectiveness is indicated, the technology is believed capable of successfully treating several compounds in the contaminant group. When the technology is not applicable, a No Expected Effectiveness rating is given. This rating applies primarily to contaminants that are not biodegradable (e.g., asbestos and radioactive materials). Experts also believe that composting is generally not effective for halogenated and nonhalogenated volatiles because they will normally volatilize before they have the opportunity to biodegrade. This does not mean that composting cannot be applied to soils that contain volatile organic compounds (VOCs) and SVOCs if the VOCs are collected and treated. However, the presence of VOCs in significant concentrations likely precludes the use of windrow composting since VOC collection is not feasible.

Limitations

In general, composting is slower than many other nonbiological soil remediation technologies, but its application can be flexible and cost-effective. Batch remediation times ranging from 2 to 20 weeks are common for composting hazardous wastes. However, the compost may require several years of maturation or storage to decrease the residual concentrations of contaminants to environmentally acceptable levels.

Site- and contaminant-specific factors impacting contaminant availability and microbial activity may limit the application of composting. Site-specific factors include soil characteristics, climatic conditions, and location of contamination at the site. Contaminant-specific factors include volatility, biotoxicity, polarity, and chemical structure.

Site-Specific Factors

While the soil characteristics discussed in the following paragraphs potentially limit the applicability of composting to some sites, it is important to note that all of these soil characteristics can be modified. A discussion of some of the techniques used to modify soil characteristics is presented in the Technology Description section. It should also be noted that other ex situ technologies are affected by these same soil characteristics.

Soil characteristics that may affect the applicability of composting include particle size distribution, moisture content, pH, and nutrient levels. Particle size can impact mixing, moisture holding capacity, oxygen transfer rates, and contaminant adsorption and availability. Wet clays can be difficult to mix with amendments, and lumping can result. Lumping can limit oxygen transfer rates and contaminant availability, resulting in incomplete treatment. Clays and humic materials have high moisture holding capacities; excessive moisture can fill void spaces and limit oxygen transfer. Sandy soils have low moisture holding capacity and may drain quickly, resulting in drying of upper regions of compost piles. Localized drying can reduce microbial metabolism, resulting in incomplete contaminant degradation. Because of increased surface area and soil particle charges, contaminant sorption can be problematic in clayey soils and soils with high humic content [11, p. 33]. If contaminants are strongly sorbed onto soil particles, contaminant desorption rates are reduced. The remediation rate may be limited by the slow kinetics of contaminant desorption rather than biodegradation.

Soil pH, moisture content, nutrient deficiencies, temperature, and oxygen concentration can affect the diversity and activity of the microbial population and suppress specific contaminant degraders. If the process is poorly controlled so that wide variations exist, inconsistent or undesirable results will be obtained due to fluctuations in biological activity. Oxygen deficiencies will promote anaerobic microorganisms and inhibit aerobic respiration, the predominant form of microbial metabolism in composting. The biodegradation of chemical contaminants that are recalcitrant to aerobic decomposition (e.g., polychlorinated organic compounds) may be initiated or occur more readily under anaerobic conditions. Pockets of anoxic conditions may exist within agglomerates and aggregates in compost piles even under bulk aerobic conditions. Complete breakdown or mineralization of substituted aromatics is not common under anaerobic conditions.

The location of contaminants at a site will affect the feasibility and costs of implementing composting. Since composting is an ex situ technology, it is limited to fairly shallow soils (e.g., less than 50 feet deep) that can be excavated economically. As with other ex situ technologies, composting is not practical for use when contaminants are located under buildings or other structures.

Additional site-specific limitations, such as accessibility and odor control problems, are discussed in the Site Requirements section of this bulletin.

Contaminant-Specific Factors

Contaminant volatility will limit the residence time of chemicals in composting systems. These systems frequently achieve temperatures in excess of 40°C within the first week of operation, and may operate for several months at temperatures in excess of 60°C. At these elevated temperatures, a large portion of any VOCs is volatilized before significant biodegradation can occur. Soils that contain both VOCs and less volatile contaminants can be composted, and volatilized contaminants can be collected from the air. However, even though many VOCs are biodegradable, composting is not be recommended for soils containing primarily VOCs. At elevated temperatures, certain VOCs can pose threats of fire or explosion in enclosed systems unless proper controls are installed.

As with any biological treatment, biotoxicity of certain contaminants may limit the applicability of composting. Treatability studies will be required to determine if the contaminant types or concentrations inhibit microbial growth or activity in composting systems.

Polarity and chemical structure impact the solubility and bioavailability of contaminants. Types and positions of substitution groups can affect biodegradation rates and metabolic pathways. A detailed discussion of this subject is beyond the scope of this document. Consultation with bioremediation experts and performance of site-specific treatability studies are recommended.

Technology Description

Composting can be distinguished from other forms of biological remediation by the use of bulking agents that increase soil porosity and, in some cases, provide a readily available carbon source. Frequently, other easily-degradable carbon sources are added to sustain microorganisms capable of degrading hazardous waste constituents associated with a solid medium, such as soil. Composting biodegrades organic matter utilizing solid-, liquid-, and gas-phase processes. The solid phase provides physical support for biofilm growth, a source of organic and inorganic nutrients, a sink for metabolic products, and thermal insulation [12, p. 2]. The liquid phase, which is a surficial layer on the solid, provides a matrix for exchange of gases, nutrients, and metabolic products. The gas phase delivers oxygen and provides a sink for gaseous metabolic products, such as carbon dioxide and ammonia. The gas phase also serves as the primary heat sink through evaporative cooling.

Figure 1 is a schematic representation of the composting process. Pretreatment for composting consists of excavating the contaminated material and screening or shredding the large debris to a smaller size. If the contaminant is present as free product, it should be removed before composting is initiated. Amendments such as bulking agents and/or organic material are then added to the soil. Microorganisms can be added, although indigenous organisms are normally sufficient to achieve the desired biodegradation. The material is then left to compost in vessels, windrows, or static piles. Oxygen is added to the compost by forced aeration in static piles or in-vessel systems, or by mixing and passive diffusion in windrows. Water can be added to the compost to achieve optimum moisture content, and nitrogen (N) and phosphorus (P) can be added if the compost is nutrient-poor, which is often the case. After the desired composting end-point is reached, bulking agents can sometimes be separated from composted material and recycled, and composted material can be used to inoculate more soil. Easily degradable bulking agents will not be separable. Finally, composted material can be put into piles for additional curing, treated by another technology as part of a treatment train, or relocated to onsite or offsite disposal areas.

The major form of microbial metabolism in the composting process is aerobic respiration, although mass transfer limitations within the composting mass may cause anaerobic zones. The anaerobic zones of compost systems may facilitate degradation of compounds, such as DDT and dieldrin, making them more susceptible to aerobic decomposition [13, p. 32]. However, since there is little information available regarding anaerobic composting, this bulletin focuses on aerobic processes.

The composting process is essentially microbiological, mediated by microbial populations that are classified as mesophiles or thermophiles. Mesophilic microbes are those with an optimum temperature range of 25° to 40°C; thermophilic microbes have an optimum temperature range of 40° to 60°C [14, p.1].

During composting, there are four major microbiological phases that are identified by temperature. The optimal degradation temperature is contaminant-specific. Temperature ranges cited for mesophiles and thermophiles vary between references, resulting in a small overlap in these phases. In static pile and in-vessel composting, air flow rates can be used to influence temperature. Air flow is often intermittent, and the inflow point is sometimes varied to prevent the bed from drying out at the point of air entry.

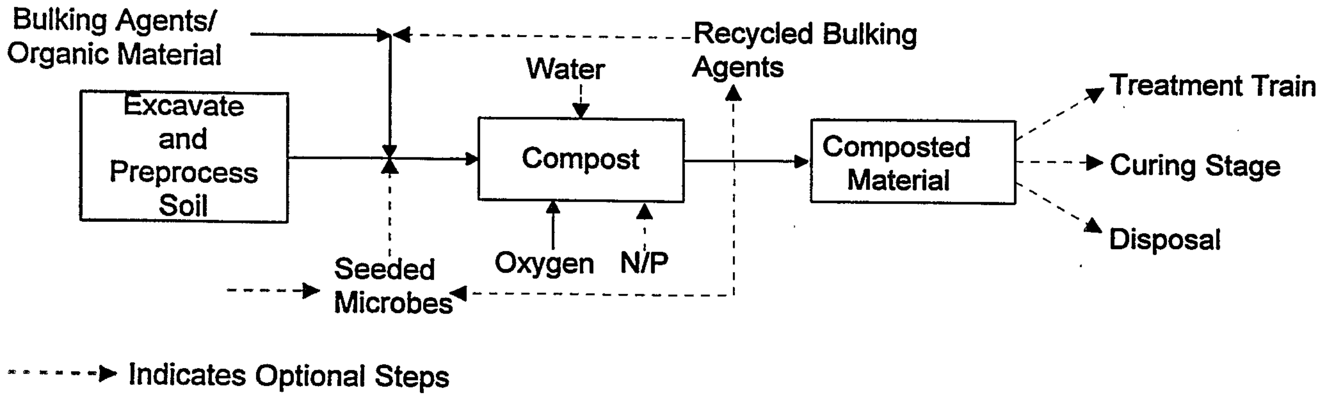

Figure 1. Schematic of Composting Process.

The first of the four phases is the mesophilic stage, in which temperatures range from 8° to 45°C. The greatest microbial diversity exists in this stage. The second phase is the thermophilic stage, in which temperatures are above 40°C [14, p. 229][15, p. 1]. Certain degraders will be inhibited by thermophilic temperatures. Few thermophilic microorganisms have been identified that are capable of degrading or mineralizing man-made compounds. The role of the thermophilic phase of the composting process continues to be investigated. The third phase is the cooling stage, in which there is a microbial recolonization including mesophilic fungi, the spores of which withstood the thermophilic stage. The fourth and final phase is the maturation phase, in which most of the digestible organic material has been consumed, and the composted material becomes stable [14, p. 228]. Recalcitrant compounds will continue to be degraded by organisms such as fungi during the fourth phase. The maturation phase should be extended until concentrations of recalcitrant compounds are below target levels.

The optimum moisture content for composting varies depending on the water-holding capacity and porosity of the compost mixture and the type of composting technology being implemented, but a moisture content of less than 40 percent (by weight) frequently inhibits bacterial activity [13, p. 32]. For composting of soils mixed with amendments, the optimum moisture content is typically 40 to 60 percent (by weight). Periodic addition of water is required for nearly all composting operations; however, excessive water content slows down gas diffusion and may lead to the establishment of anaerobic conditions and associated odor control problems. Excessive water addition can also lead to formation of leachate that must be collected and managed.

Adequate oxygen supply to the microbes is essential for composting. Oxygen can be supplied within the compost using forced air (i.e., a blower) or passive diffusion (aided by turning over or agitating the material). However, these oxygen addition techniques will be inadequate unless the compost mixture has adequate porosity, which is defined as the ratio of the volume of voids to the total volume of soil. A porosity of 0.30 to 0.35 is optimum for composting processes. Other optimum operating conditions for composting are a pH of 6 to 8 and an available carbon to nitrogen to phosphorus (C:N:P) ratio of 100:4:1 by weight [16, p. 249][17, p. 57].

A large portion of the compost mixture must contain readily biodegradable solid organic material. Such substances include vegetation and food processing wastes (e.g., sawdust, grass clippings, alfalfa, potato peels, apple peels, etc.), which are organic materials rich in carbon. In most cases, additional inorganic nutrients (primarily nitrogen and phosphorus) are also needed to provide optimal conditions for microbial metabolism. This need can be addressed by the addition of fertilizer or manure [18, p. 92]. Grass clippings and alfalfa can play a dual role, as they are rich in carbon and nitrogen and can be added as a nitrogen amendment to carbon-rich substrates. The organic material may also increase the porosity of the compost mixture.

When the mixture of soil and organic material has a low porosity, a bulking agent should be added [19, p. 2332]. Ideal bulking agents provide ample porosity under all moisture conditions, are absorbent, and resist compaction. The bulking agent may be a slowly-degrading substance that serves as a supplemental carbon source, or it may be a nondegrading substance that can be easily recovered from the composted wastes and recycled [13, p. 32]. Suitable bulking agents include fibrous vegetation (e.g., straw), wood chips or bark, corn cobs, rice hulls, and peanut shells. Soil-to-bulking agent ratios of between 50:50 and 70:30 have been frequently applied. Recyclable bulking agents, such as wood chips, may be recovered by screening the composted wastes.

Bioaugmentation (the addition of microorganisms) is occasionally employed in composting processes, but its utility has yet to be proven and is currently an issue of controversy. Bioaugmentation may be inappropriate because introduced cultures may lack the microbial diversity that is an important factor in decomposing contaminant mixtures in natural systems. Partial return of composted product to fresh compost piles can provide beneficial inoculum.

Composting can be divided into three categories: in-vessel composting, windrow composting, and static pile composting. The remainder of this section describes these three categories. Biopiles, which do not utilize bulking agents, are also briefly described to differentiate them from composting.

In-Vessel Composting

When performing in-vessel composting, material is placed inside a large containment vessel equipped with a temperature-controlled aeration system. In-vessel composting is conducted in partially or totally enclosed vessels; however, the curing phase may take place in a static pile to reduce the residence time in the vessel. In-vessel systems can also be equipped with a mechanism that will periodically mix or agitate the composting material [18, p. 94].

The advantages of in-vessel composting include greater process control than in other types of composting and reduced space requirements. In-vessel composting may also be used for sequential treatments, such as anaerobic-aerobic phases that may promote the biodegradation of highly chlorinated organics. Use of a system in which the vessels are totally enclosed is desirable when highly toxic substances are present, or when off-gas collection is desired [18, p. 94]. This type of system controls odors better than either windrow or static pile composting [20, p. 56]. Gas exiting the reactor can be continuously monitored for oxygen, carbon dioxide, methane, and humidity. The gas stream can be passed through air pollution control equipment. Computers can monitor the system, collect data, and adjust parameters, which is useful for composting research and treatability studies and to optimize degradation rates. Disadvantages of in-vessel composting include higher capital and operating costs and a longer lead time for setup than in other types of composting. Since the system is automated, mechanical breakdown can occur. Fires can occur during in-vessel composting of mixtures composed primarily of organic materials, but are not likely during composting of soil mixtures.

Windrow Composting

In windrow composting, the material to be composted is formed into long parallel rows, which are approximately 1.4 to 1.7 meters (m) in height [7, p. 45]. Some type of containment, such as a plastic liner or a concrete pad, is typically required below the windrows. The rows, which may be watered occasionally, are periodically turned to promote aeration [18, p. 93]. Full-scale windrow composting uses specialized machines called windrow turners, commercially-available vehicles, designed to turn and shape windrows.

The advantages of windrow composting over other types of composting are low capital and operating costs, thorough blending, ease of adding water and nutrients when the windrow is broken down, and greater volumes of material treated. Disadvantages of windrows include large space requirements, difficulty in controlling fugitive emissions, and the fact that, if not covered or sheltered, windrows may be exposed to excessive rainfall and prohibitively low temperatures. The system may not be desirable if tight process control is needed. Windrow temperature is a complex function of feed material, pile depth, moisture content, nutrient content, ambient air conditions, and turning frequency. Once a windrow is constructed and the bulking agent added, the range of temperature is relatively fixed. Consequently, other composting technologies may be more appropriate than windrow composting when temperature control is important.

Static Pile Composting

In aerated static pile composting, the material to be biodegraded is mixed with an appropriate bulking agent and formed into a pile, which may be watered occasionally. Because the piles have a built-in aeration system that provides oxygen and removes heat, no turning is required. The aeration system generally consists of a series of perforated pipes located underneath or inside the pile [18, p. 93]. Air flow can be upward or downward through the pile and can be driven by positive pressure or a vacuum.

In aerated static pile composting, fairly precise temperature control is possible by manipulating the design and operating parameters of the aeration system [20, p. 56]. Aerated static piles allow better control of temperature and oxygen concentration than windrows, but less than in-vessel applications. Air can be drawn through the pile and the ventilation system can be interfaced with a biofilter for trapping and removing odors and VOCs. The cost of aerated static piles falls between windrows and in-vessel systems. Like windrows, static piles may be affected by extreme environmental temperature changes and heavy rainfall. Unlike windrows or in-vessel systems, static piles are not mixed periodically to redistribute the material.

A summary of the relative advantages and disadvantages of each of the types of composting is presented in Table 2. Although these qualitative rankings generally apply, site conditions vary, which may render them not applicable in certain situations.

Biopiles

Biopiles are outside the scope of this bulletin. Biopiles are a specialized approach to ex situ bioremediation in which bulking agents are not used. Contaminated soil is blended with nutrients and placed in the biopile to enhance contaminant degradation by soil-borne microorganisms. Exogenous microorganisms may be added to a biopile. Biopiles structurally resemble static pile compost systems with forced aeration, air usually being drawn through the pile by a vacuum. Depending on the types of soil contaminants, the operator may establish conditions in the biopile reactor to favor either anaerobic or aerobic microorganisms. Biopiles normally produce less heat than compost piles since less organic substrate is added, although significant aerobic microbial activity will produce some heat.

Table 2
Summary of Characteristics of the Different Types of Composting

Parameter	In-Vessel	Windrow	Static Pile
Temperature Control	Easy	Difficult	Moderate
Fugitive Emission Control	Easy	Difficult	Moderate
Sequential Treatment	Easy	Difficult	Moderate
Cost	High	Low	Medium
Area Requirements	Moderate	High	High

Process Residuals

Although the majority of wastes requiring disposal are generated as part of pre- and post-treatment activities, process residuals arising directly from composting may also be generated. Potential process residuals include off-gases from the composting process, excess water (from moisture addition or, in open systems, from rainfall), and the final compost mixture (including any undegraded supplements). These residuals may contain undegraded parent contaminants, partially degraded contaminants, or metabolic by-products of the degradation process. The following paragraphs discuss specific types of process residuals, their control, and their impact on disposal requirements.

Air emissions may be a concern, depending on several factors. The volatility of the parent substances, as well as potential biotransformation products, must be considered. If a mechanical aeration system is utilized, the manner in which it is operated (vacuum or forced aeration) can impact emissions [18, p. 94]. Vacuum systems can be vented through biofilters or carbon adsorption systems to remove VOCs. Totally enclosed, in-vessel composting offers easier control of air emissions. If air emissions are a problem, an emission control and treatment system will be required.

Composting systems may produce odor problems, especially when anaerobic conditions dominate. Odors can be minimized by making operational adjustments, such as increasing porosity, additional mixing, or addition of oxygen. If odor control is necessary, many of the measures recommended for control of air emissions will also reduce odors.

Excessive watering or precipitation (in open systems) will produce leachate. Any liquids exiting the composting process may contain soluble contaminants and must be collected and recycled or treated.

Contaminants may sorb onto bulking agents used in the composting process. Recyclable bulking agents should be removed and reused until site remediation is complete. They may require treatment when the composting process is complete.

Ultimately, biological technologies seek to convert hazardous contaminants into relatively innocuous end-products. If mineralization is achieved, the ultimate end-products will be carbon dioxide, water, and inorganic salts. However, a number of contaminant-specific factors may cause partial degradation to an intermediate product. Identification of intermediate products may not be practical or cost-effective. Instead, the toxicity of the composted material can be measured to ensure detoxification. If detoxification is not sufficient, further treatment of the composted material may be necessary.

The disappearance of the parent compound must also be measured. Some contaminants are not amenable to biological degradation. For contaminants that are biodegradable, microbes degrade only the biologically available fraction of the contamination. In addition, the sorption of contaminants onto the compost mixture may become a rate-limiting factor for the biodegradation process, since the desorption rates are often extremely slow.

Because composting involves the addition of amendments and bulking agents, the volume of the finished product is typically greater than the volume of untreated material. If composting does not adequately degrade the contaminants of concern, it increases the volume of waste requiring treatment or disposal.

Site Requirements

Composting is best suited for onsite treatment and is best applied at sites which are accessible to heavy equipment and have sufficient space for onsite operations. In general, significantly less area is required for mixing equipment than for the compost piles or vessels. However, space requirements increase as the complexity of the various pre- and post-treatment systems increases.

Compost piles should be constructed on a liner or bermed concrete or asphalt pad, and provisions should be made for leachate collection and treatment. Asphalt compost pads are easier and cheaper to construct than concrete pads; however, they are more permeable. A cover may be necessary to avoid agglomeration of soils due to rainfall and to prevent wind erosion. Even if agglomeration is not a problem, a cover may be more cost-effective than collecting and treating leachate caused by heavy rainfall. If periods of heavy rainfall or extremely cold conditions are expected, a cover may be required or the composting system may be housed in a ventilated building.

Regulatory Considerations and Response Actions

Federal mandates can have a significant impact on the application of composting technologies. RCRA Land Disposal Restrictions (LDRs) that require treatment of wastes to Best Demonstrated Available Technology (BDAT) levels prior to land disposal are considered to be Applicable or Relevant and Appropriate Requirements (ARARs) for CERCLA response actions. Composting can produce a treated waste that meets treatment levels set by BDAT, but not in all cases. The ability to meet required treatment levels depends on the specific waste constituents and the waste matrix. In cases where composting does not meet these levels, it still may be selected in certain situations for use at the site if a treatability variance establishing alternative treatment levels is obtained. Treatability variances are justified for handling complex soil and debris matrices. The following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions" (OSWER Directive 9347.06FS, September 1990) [21], and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.06BFS, September 1990) [22].

When determining performance relative to ARARs and BDAT, emphasis should be placed on assessing the risk presented by a bioremediation technology. As part of this effort, risk assessment schemes, major metabolic pathways of selected hazardous pollutants, human health protocols for metabolite and pathogenicity tests, and fate protocols and issues for microorganisms and metabolites must be assessed [23]. Baseline and final toxicity testing can be an important tool in verifying achievement of cleanup goals established using ecological risk assessment.

Performance Data

Composting has been used to remediate three sites; however, reports summarizing performance data were only available from one of these sites. This section presents performance data for this site and four composting demonstrations. The results presented are based on available information. It was beyond the scope of this project to review quality assurance data and validate analytical results. Therefore, the quality of these data cannot be determined. As with most large-scale studies (including other technologies) mass balance closure of targeted pollutants has not been provided for these case studies. Therefore, it is difficult to determine if contaminant loss is attributable to degradation, sorption to the compost mixture, or volatilization.

Indiana Woodtreating Corporation Site

Aerated static pile composting was used as a remedy at the Indiana Woodtreating Corporation Site in Bloomington, Indiana. Soils were contaminated with creosote to depths ranging from the surface to 12 feet below the surface. Total PAH (TPAH) concentrations in the soil were approximately 20,410 mg/kg. Action levels for the site were 500 mg/kg TPAHs and 100 mg/kg for each of the carcinogenic PAHs. Contaminated soil was excavated, dried when necessary, screened to remove rocks larger than 3 inches in diameter, and mixed with amendments. The optimum composting mixture for every 100 tons of soil was determined in treatability tests to be 5 rolls of straw, 5 bales of horse manure, 200 pounds of urea fertilizer (37-0-0), and 100 pounds of ammonium nitrate fertilizer (34-0-0). The weights of the straw and manure were not provided in the report. Rototillers and tractors were used to mix the piles.

The final design of the compost piles consisted of 4-inch perforated and corrugated polyvinyl chloride (PVC) piping for aeration and 3/4-inch PVC piping for watering. Dimensions of piles were not given, but 22,000 tons of contaminated soil were treated in nine piles. Analytical results from samples collected biweekly indicated that PAH concentrations decreased exponentially and the microbial population was high. Compost piles were maintained for about 1 year, at which time contaminant concentrations in the piles were consistently below the action levels for the site. The composted material was then landfarmed for approximately 1 additional year in a 2-foot-thick layer. TPAH concentrations, after the year of landfarming was complete, fell below 100 mg/kg in all landfarm areas [2].

Umatilla Depot Activity Site — Windrow

A 40-day, full-scale demonstration of windrow composting was performed at the Umatilla Depot Activity Site. The windrow was turned once each day, and its internal temperature was recorded before and after turning. Although the turning process typically reduced the internal temperature by at least a few degrees, the internal temperature achieved was between 40° and 55°C from Day 6 through Day 24. The composting mixture consisted of 30.0 percent soil, 24.4 percent manure, 10.0 percent vegetable waste, and 35.6 percent alfalfa/sawdust, by volume. Table 3 lists the contaminant concentrations and reductions on various days of the study. The contaminant concentrations for Day 0 describe the compost mixture shortly after it was prepared (rather than the soil before the amendments were added) [24]. Concentrations of four 2,4,6-trinitrotoluene (TNT) intermediate products were also measured. Two of these were below detection limits on Day 0, and the other two decreased as the study progressed [4].

Toxicological studies were performed on leachate prepared from the compost mixture using EPA Method 1312: Synthetic Precipitation Leaching Procedure (SPLP) [25]. The aquatic toxicity tests measured the mortality and inhibition of reproduction of the fresh water crustacean *Ceriodaphnia dubia*. Results indicate that the compost leachate concentration (as a percent of full-strength) required to kill 50 percent of the test organisms in 7 days (LC_{50}) increased from 4.0 percent on Day 1 to 47.5 percent on Day 40. The concentration of compost leachate required to lower mean reproduction to 15 offspring per female in 7 days (SR_{15}) increased from 1.9 percent on Day 1 to 14.2 percent on Day 40. The study concluded that biotransformation of the explosives to less toxic compounds had occurred [24, p. 8-1][26, p. 123].

Umatilla Depot Activity Site — In-Vessel

A pilot-scale demonstration was performed at the Umatilla Depot Activity site using a 7-cubic-yard, mechanically-agitated, in-vessel composting system to remediate soil contaminated with explosives [TNT; hexahydro-1,3,5-trinitro-1,3,4-triazine (RDX); and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX)]. The temperature of the compost mixture was kept at or below 55°C using forced aeration, and the moisture content was maintained between 45 and 50 percent. Three different amendment mixtures were used. Mix A contained (by volume) 30 percent sawdust, 15 percent apple pomace, 20 percent chicken manure, and 35 percent chopped potato. Mix B consisted of 50 percent horse manure/straw, 10 percent buffalo manure, 32 percent alfalfa, and 8 percent horse feed. Mix C contained 22 percent sawdust, 6 percent apple pomace, 17 percent chopped potato, 22 percent alfalfa, and 33 percent cow manure. Table 4 summarizes the amount of soil and amendment mix used, percent disappearance of contaminants, and the duration of each of four studies. The majority of the contaminants that disappeared did so within the first 10 days. The pretreatment basis for the contaminant disappearance

Table 3
Contaminant Reductions [24]

Day	TNT mg/kg	RDX mg/kg	HMX mg/kg	Percent Disappearance		
				TNT	RDX	HMX
0	1,563	953	156	0.0	0.0	0.0
5	101	1,124	158	93.5	0.0	0.0
10	23	623	119	98.5	34.6	23.7
15	19	88	118	98.8	91.7	24.4
20	11	5	2	99.3	99.5	98.7
40	4	2	5	99.7	99.8	96.8

Table 4
Percent Disappearance of Explosives [4][27]

Soil in Compost, Percent	Amendment Mix	Percent Disappearance			
		TNT	RDX	HMX	Duration of Study
10	A	97	90	29	44 days
10	B	99	99	95	43 days
25	C	99	97	68	44 days
40	C	97	18	0	45 days

calculations (concentrations in unamended soil or compost mixture) is not specified, so it is not clear whether a portion of the reported disappearances is due to dilution of soil by amendments [27].

Louisiana Army Ammunitions Plant (LAAP)

A field-scale demonstration was conducted at the Louisiana Army Ammunitions Plant (LAAP) using aerated static piles. Lagoon sediments on the site were contaminated with the explosives TNT, RDX, HMX, and tetranitro-N-methyl aniline (tetryl). Initial concentrations in the sediment were 56,800 mg/kg TNT; 17,900 mg/kg RDX; 2,390 mg/kg HMX; and 650 mg/kg tetryl. The compost pile was formed on a concrete test pad, which had drainage channels leading to a sump. The water from the sump was reapplied to the compost pile. The pile weighed 4,400 kg and contained 24 percent sediments, 10 percent alfalfa, 25 percent straw/manure, and 41 percent horsefeed, by weight. Fertilizer (13:13:13) was also added. The temperature was kept close to 55°C. Initial contaminant concentrations in the compost were 11,840 mg/kg TNT; approximately 5,300 mg/kg RDX; and approximately 750 mg/kg HMX. Final contaminant concentrations were 3 mg/kg TNT; 45 mg/kg RDX; and 26 mg/kg HMX. Tetryl was below detection limits in all samples. The half-life was 12 days for TNT, 17 days for RDX, and 23 days for HMX [28][29, p. 137]. The treated material was analyzed for several TNT transformation products (2-amino-4,6-dinitrotoluene; 4-amino-2,6-dinitrotoluene; 2,4-diamino-6-nitrotoluene; and 2,6-diamino-4-nitrotoluene). Concentrations of transformation products started out low, increased the first few weeks of the study, and then declined thereafter [29, p. 137].

Badger Army Ammunition Plant (BAAP)

A field-scale demonstration was performed at the Badger Army Ammunition Plant (BAAP) in Baraboo, Wisconsin using aerated static piles. Soils at this site are contaminated with the propellant nitrocellulose (NC). Four aerated static piles were formed; the composition (on a weight basis) of these piles was: two piles with 19 percent soil, 11 percent alfalfa, 45 percent manure, 17 percent horsefeed, and 8 percent wood chips; one pile with 22 percent soil, 8 percent alfalfa, 51 percent manure, 16 percent horsefeed, and 3 percent wood chips; and one pile with 33 percent soil, 5 percent alfalfa, 44 percent manure, 13 percent horsefeed, and 5 percent wood chips. Temperature was controlled by panel-mounted Fenwal 551 thermistor-sensing temperature controllers. Pile 1 was maintained at approximately 35°C until Day 57 when temperatures climbed and ranged from 60° to 65°C between Day 75 and Day 94, after which temperatures declined. Piles 2, 3, and 4 reached 55° to 65°C within 5 days; the temperature declined after Day 65. Table 5 shows the results of the study [29, p. 137].

Table 5
Results of BAAP Study [29, p. 137]

Pile Number	NC mg/kg Day 1	NC mg/kg Day 100	Percent Reduction
1 (19% soil)	4,933	133	97.3
2 (19% soil)	3,093	54	98.3
3 (22% soil)	7,907	30	99.6
4 (33% soil)	13,086	16	99.9

Technology Status

Composting has been either considered or selected as the remedial technology at 10 CERCLA, RCRA, other federal facility, State, and Canadian Sites [1][2][3]. As of January 1996, the status of the sites was as follows: full-scale remediation was completed at three sites; full-scale remediation was in progress at two sites; two were in the design stage of full-scale remediation; and three were in the predesign stage. Table 6 lists the location, primary contaminants, treatment employed, and status of these sites. Table 6 is based on information obtained from the August 1995 edition of "Bioremediation in the Field" [1] and a draft report on the Indiana Woodtreating Corporation site [2]. This table was modified based on phone calls made to the various site contacts. Where possible, original sources were obtained and used to verify site information [3].

Aerated static pile, windrow, and in-vessel composting technologies are all commercially available at field-scale. Mobility or transportability is not generally a constraint, since minimal equipment is required with the exception of in-vessel systems. Specific equipment requirements are dependent upon the composting technology selected. Depending on size, in-vessel systems may be transportable or may be assembled onsite. Aeration systems for static piles typically require onsite construction. The windrow turners used in full-scale windrow composting systems are transportable.

Most of the hardware components of composting systems are available off-the-shelf and present no significant availability problems. One of the advantages of composting is the short lead time needed to set up a working facility. Almost no construction is needed for windrow and aerated static pile composting. Bulldozers and compost screens are readily available, but sophisticated windrow turners and mixers may require some lead time. Modified bulldozers and front-end loaders can be used to make windrows and static piles. Custom-made mixers require the longest lead time. Selected cultures are available for bioaugmentation; however, their utility is unproven. Nutrient and bulking additives can frequently be acquired from nearby sources (e.g., farms, horse stables, food processing plants, and sawmills).

Composting technologies provide cost-effective treatment for selected hazardous waste constituents. This can be attributed in part to low capital costs, and in part to low operation and maintenance requirements. It is difficult, however, to generalize treatment costs since site-specific characteristics can significantly impact costs, and many cost estimates neglect one or more elements of the overall cost (e.g., excavation, energy usage, disposal of residuals). Initial concentrations and volumes, clean-up requirements, and air emissions control systems will impact final treatment costs. The types and local availability of amendments employed can also impact operational costs and costs associated with equipment and manpower required during their application.

The composting technology (i.e., in-vessel, static pile, or windrow composting) chosen also affects the cleanup cost. In general, the highest capital and energy costs are associated with in-vessel composting. Capital and energy costs for aerated static pile composting are typically lower than those for in-vessel composting but higher than those for windrow composting. Windrow composting is generally the least expensive composting technology, although full-scale windrow composting typically requires the purchase and operation of a windrow turner.

Costs for treating 20,000 tons of explosives-contaminated soil over a 5-year period have been estimated for windrow composting, aerated static pile composting, in-vessel composting, and incineration [30]. The cost estimates for the three composting technologies are based on the results of pilot- and field-scale studies conducted at the Umatilla Depot Activity Site, including the windrow and in-vessel studies described in the Performance Data section of this bulletin. Based on these studies, the three cost estimates assume compost mixtures that are 30 percent soil (by volume). The composting cycle times are designed, based on treatability study results, to achieve 99.5 percent removal of TNT [30]. The three composting cost estimates each include excavation, capital (any required site construction, equipment, etc.), operation and maintenance (both labor and materials), monitoring, sampling and analysis, onsite disposal, electric, water, overhead, and contingencies [30].

The cost estimate for windrow composting assumes that the windrows will be constructed in an enclosed structure on a RCRA-approved pad. It also assumes that aeration and mixing will be provided by daily turning with a commercially available compost turner. The total 5-year project cost for windrow composting is estimated to be $4,222,000, which is $211 per ton of soil treated [30].

Table 6
Field Applications of Bioremediation [1][2][3]

Site Location	Primary Contaminants	Status	Treatment
Indiana Wood Treating Bloomington, IN	Soil (TPAHs[a], up to 357 g/kg). Volume: 22,000 tons.	Laboratory-scale studies were started 04/92 and completed 06/92. Pilot-scale studies were started 06/92 and completed 07/92. Full-scale remediation (composting and landfarming) were started 11/92 and completed 08/94.	Aerated static pile composting followed by landfarming; indigenous organisms. Amendments were straw, horse manure and two types of fertilizer.
Amoco Refinery Sugar Creek, MO	Soil (phenanthrene, pyrene, naphthalene, toluene, xylene) Volume: 120,000 yd^3.	Laboratory-scale and pilot-scale studies have been completed. Full-scale remediation has been underway since 06/94. 50,000 yd^3 remediated as of 12/95.	Aerated static pile; indigenous organisms. Composting batches of 7,000 yd^3 at a time (including bulking agents). Added 25-50 percent shredded wood and also added nutrients.
Sabliere Thouin Assomption, Quebec, Canada Development and Demonstration of Site Remediation Technology (DeSRT) Program	Soil (BTEX[a], 135 mg/kg; styrene, 50 mg/kg; chlorobenzene, 10 mg/kg; TPAHs, approx. 430 mg/kg) TCE[a] or PCE[a] appear randomly distributed on the site. Volume: 330 yd^3 (250 m^3)	Laboratory-scale studies were started 05/92 and completed 08/93. Pilot-scale studies have been underway since 05/94. Full-scale remediation is being considered.	Aerated static pile, nutrient addition [urea and Daramend (Grace Dearborn amendment)]. Indigenous organisms. Experimenting with various types of amendments in pilot-scale studies.
Novak Farm Chenango County, NY	Soil (SVOCs, 50 mg/kg; xylene, 1.2 mg/kg) Volume (vadose soil): 30,000 yd^3 (saturated soil): 25,000 yd^3 (19,000 m^3)	Laboratory-scale studies were completed 12/93. Full-scale remediation is planned to begin 4/96. Currently in design.	Full-scale remediation will be one of two designs. Either using windrows with vermiculite and lime amendments in a pug mill for a cost of $100/ton or placed in giant biocell in ground for 1 year using woodchips as amendments at an estimated cost of $65/ton. Aerobic conditions, indigenous organisms.
Owens-Corning[b] Kansas City, KS	Soil (formaldehyde, 1 mg/kg) Volume: 300 yd^3	Full-scale remediation was completed 07/92.	Pile, aerobic conditions, indigenous organisms.
Prince Edward Island Prince Edward Island, Canada, Environment Canada/Canada Petroleum Products Institute	Soil (petroleum) Volume: 150 yd^3 (120 m^3)	Pilot-scale studies have been underway since 09/94 using various ratios of municipal solid waste to soil. Full-scale remediation is planned.	Aerated static pile, aerobic conditions, indigenous organisms.
Wheeling-Pittsburgh Steel Allenport, PA	Soil (TPHs[a], 500 mg/kg) Volume: 1,800 yd^3 (1400 m^3)	Laboratory-scale studies were started 04/94 and completed 05/94. Full-scale remediation is planned. Design is complete. Baseline data are being updated prior to anticipated remediation.	Aerated static pile, indigenous organisms.
Boucherville Electrical Station Quebec, Canada	Soil (transformer oil, 5,000 mg/kg) Other contaminants: inorganic contaminants Volume: 650 yd^3 (500 m^3)	Laboratory-scale and pilot-scale studies were started 01/91 and completed 01/92. Full-scale remediation was completed 12/92.	Aerated static pile. Indigenous organisms. Woodchips and straw added as amendments.

Table 6 (continued)

Site Location	Primary Contaminants	Status	Treatment
Umatilla Depot Activity Site, Hermiston, OR	Soil (TNT, 1,563 mg/kg; RDX, 953 mg/kg; HMX 156 mg/kg)	Full-scale demonstration was started 4/92 and completed 12/92. Full-scale remediation was started March 1995.	Windrow. Indigenous organisms. Manure, vegetable waste, alfalfa, and straw added as amendments.
Air Products and Chemicals, Inc. Pace, FL	Soil (DNT[a], 2.34 mg/kg) Volume of soil is unknown (has not been excavated)	Laboratory-scale and pilot-scale studies are planned. Full-scale remediation is planned. Currently in predesign.	Aerated static pile, nutrient and bulking agent addition. Aerobic and anaerobic conditions, exogenous and indigenous organisms.

a Abbreviations: TPAH - Total polycyclic aromatic hydrocarbons; BTEX - benzene, toluene, ethylbenzene, and xylene; TCE - Trichloroethylene; PCE - Perchloroethylene; TPH - Total petroleum hydrocarbons; DNT - Dinitrotoluene.

b A site contact could not be reached; therefore, site details are unknown.

The cost estimate for aerated static pile composting assumes that the static piles will be contained within wooden, rectangular bins constructed in an enclosed structure on a RCRA-approved pad. The total 5-year project cost for aerated static pile composting is estimated to be $5,659,000, which is $283 per ton of soil treated [30].

The cost estimate for mechanically-agitated in-vessel composting assumes that composting will be conducted in a reactor constructed outside on a concrete foundation. The total 5-year project cost for in-vessel composting is estimated to be $6,280,000, which is $314 per ton of soil treated [30].

Onsite incineration costs were developed for comparison to the composting cost estimates. The incineration costs include mobilization and demobilization of the incineration unit, but do not include excavation of the contaminated soil or disposal of the treated material. For comparison purposes, "treatment only" costs were developed for each of the composting technologies. The "treatment only" costs include all of the items listed above except for excavation and disposal. A comparison of "treatment only" costs is presented in Table 7 [30].

Table 7
Estimated "Treatment Only" Costs for Remediation of 20,000 Tons of Explosives-Contaminated Soil in a 5-Year Period [30]

Technology	Cost per Ton
Windrow Composting	$187
Aerated Static Pile Composting	$236
Mechanically-Agitated In-Vessel Composting	$290
Onsite Incineration	$300

EPA Contact

Technology-specific questions regarding composting may be directed to:

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REFERENCES

1. U.S. Environmental Protection Agency. Bioremediation in the Field. EPA/540/N-95/500, August 1995.

2. U.S. Environmental Protection Agency. Draft: On-Scene Coordinator's Report - Removal Action at the Indiana Woodtreating Corporation Site, Bloomington, Indiana site, ID # R.D, 1995.

3. Telephone conversations with various site contacts in January 1996.

4. U.S. Army Corps of Engineers, Toxic and Hazardous Materials Agency. Optimization of Composting for Explosives Contaminated Soil, Final Report. Report No. CETHA-TS-CR-91053, November 1991.

5. Moore, R.E. Enhanced Bioactivity Treats Hydrocarbon-Contaminated Soils. The National Environmental Journal, January/February 1992. pp 34-37.

6. Michel, F.C., C.A. Reddy, and L.J. Forney. Microbial Degradation and Humification of the Lawn Care Pesticide 2,4-Dichlorophenoxyacetic Acid During the Composting of Yard Trimmings. Applied and Environmental Microbiology, July 1995. pp. 2566-2571.

7. Haug, R.T. The Practical Handbook of Compost Engineering. Lewis Publishers, Inc., Boca Raton, Florida, 1993.

8. Hoitink, H.A.J. and H.M. Keener (eds.). Science and Engineering of Composting: Design, Environmental, Microbiological, and Utilization Aspects (An International Symposium). Renaissance Publications, Worthington, Ohio, 1993.

9. Savage, G., L.F. Diaz, and C.G. Golueke. The Linkage of Composting and Bioremediation. BioCycle, October 1995. p. 62.

10. U.S. Environmental Protection Agency. Technology Screening Guide for Treatment of CERCLA Soils and Sludges. EPA/540/2-88/004, OSWER, Cincinnati, Ohio, 1988.

11. Sims, R.C., D.L. Sorensen, J.L.Sims, J.E. McLean, R. Mahmood, R.R. Dupont, and K. Wagner. Review of In-Place Treatment Techniques for Contaminated Surface Soils. EPA-540/2-84-003b, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1984.

12. Finstein, M.S. and J.A. Hogan. Integration of Composting Process Microbiology, Facility Structure and Decision-Making. In: Science and Engineering of Composting: Design, Environmental, Microbiological and Utilization Aspects, 1993. pp. 1-23.

13. Savage, G.M., L.F. Diaz, and C.G. Golueke. Disposing of Organic Hazardous Wastes by Composting. BioCycle, January/February 1985. pp. 31-34.

14. Fogarty, A.M. and O.H. Tuovinen. Microbiological Degradation of Pesticides in Yard Waste Composting. Microbiological Reviews, June 1991. pp. 225-233.

15. Bardos, R.P. and J.M. Lopez-Real. The Composting Process: Susceptible Feedstocks, Temperature, Microbiology, Sanitization and Decomposition. Workshop: Compost in Waste Management, 1988.

16. Yusuf M., J.H. Johnson, Jr., and L. Wan. Detoxification of Contaminated Sludge via In-Vessel Composting. In: Proceedings of the 23rd Mid-Atlantic Industrial Waste Conference, Pittsburgh, Pennsylvania, 1991. pp. 247-258.

17. Golueke, C.G. Bacteriology of Composting. BioCycle, January 1992. pp 55-57.

18. Ziegenfuss, P.S., R.T. Williams, and C.A. Myler. Hazardous Materials Composting. Journal of Hazardous Materials, Vol. 28, 1991. pp 91-99.

19. Adenuga, A.O., J.H. Johnson, Jr., J.N. Cannon, and L. Wan. Bioremediation of PAH-Contaminated Soil via In-Vessel Composting. Water, Science, and Technology, 26(9-11), 1992. pp. 2331-2334.

20. Davis, K.J. and D.J. Russell. Soil Treatment Technologies Combined. Pollution Engineering, July 1993. pp 54-58.

21. U.S. Environmental Protection Agency. Superfund LDR Guide #6A (2nd Ed.): Obtaining a Soil and Debris Treatability Variance for Removal Actions. Directive 9347.3-06FS, 1990.

22. U.S. Environmental Protection Agency. Superfund LDR Guide #6B: Obtaining a Soil and Debris Treatability Variance for Removal Actions. Directive 9347.3-06BFS, 1990.

23. Day, S.M., K.J. Malchowsky, T.W. Schultz, P. Sayre, and G.S. Sayler. Draft Issue Paper: Potential Risks, Environmental and Ecological Effects Resulting from the Use of GEMS for Bioremediation. U.S. Environmental Protection Agency, Office of Toxic Substances, 1993.

24. U.S. Army Environmental Center. Windrow Composting Demonstration for Explosives-Contaminated Soils at the Umatilla Depot Activity, Hermiston, Oregon. Report No. CETHA-TS-CR-93043, Aberdeen Proving Ground, Maryland, August 1993.

25. U.S. Environmental Protection Agency. Test Methods for Evaluating Solid Waste (SW-846), 3rd. Ed., through Update IIB, 1995.

26. Keehan, K.R. Seminar on Technologies for Remediating Sites Contaminated with Explosive and Radioactive Wastes, Sacramento, California. U.S. Army Environmental Center, Technical Support Division, Aberdeen Proving Ground, Mary and, June 1993.

27. Federal Remediation Technologies Roundtable. Aerobic Composting Optimization: Explosives (TNT, RDX, HMX) in Contaminated Soil and Sediment. pp 8-10.

28. Federal Remediation Technologies Roundtable. Aerated Static Pile Composting: Explosives (TNT, TDX, HMX) in Lagoon Sediments. pp. 2-4.

29. Williams, R.T., P.S. Ziegenfuss, and W.E. Sisk. Composting of Explosives and Propellant Contaminated Soils Under Thermophilic and Mesophilic Conditions. Journal of Industrial Microbiology, Vol. 9, 1992. pp. 137-144.

30. U.S. Army Environmental Center. Windrow Composting Engineering/Economic Evaluation. Report No. CETHA-TS-CR-93050, Aberdeen Proving Ground, Maryland, May 1993.

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